Local Flame Displacement Velocity of Hydrogen Added Lean Methane Turbulent Flame

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Keywords: Turbulent Propagating Flame, Local Flame Displacement Velocity, Hydrogen Addition, PreferentialDiffusion, Markstein Number, Laser Tomography

INTRODUCTION

The lean-burn technique is one of the promising techniques to protect the environmental problems and to save energy. However, this technique still has some difficulties concerning combustion itself such as the substantial decrease in the burning velocity and the large increase in the misfire probability as fuel/air ratio of the mixture approaches the lean limit. In our previous studies [1-2], it has shown that such difficulties can be solved by adding hydrogen to lean hydrocarbon/air mixtures. By the addition of only a small amount of hydrogen to the lean mixture, the turbulent burning velocity is substantially increased and the lean limit is greatly extended at the same time. In the studies, the improving mechanism can be explained with attention to the effect of preferential diffusion depending on the molecular diffusivity of reactants. The change in the local burning velocity caused by the preferential diffusion affects substantially the turbulent burning velocity. Thus, it is important for establishing the turbulent burning velocity model of hydrogen added hydrocarbon mixtures that the local burning velocity characteristics of those mixtures are comprehended.

The present study is performed to investigate directly the local flame properties of turbulent propagating flame at the same weak turbulence condition (u'/S_{L0}=2.3), in order to clarify directly the influence of the addition of hydrogen to lean methane mixtures on its local burning velocity. Hydrogen added lean methane mixtures having nearly the same laminar burning velocity with different rates of addition of hydrogen are prepared. A two-dimensional sequential laser tomography technique is used to obtain the temporal statistical relationship between the flame shape and the flame displacement. In order to examine the local burning velocity, the local flame displacement velocity S_F is quantitatively obtained as the key parameters of the turbulent combustion. The obtained S_F is discussed by the concept of preferential diffusion and also by the Markstein number.

EXPERIMENTAL METHODS

Apparatus and Procedure

The combustion chamber used in the present study is a nearly spherical vessel having a mean inner diameter of approximately 100 mm as shown in Fig.1. The combustion chamber has four transparent 85-mm-diameter windows located on four rectangular sides of the chamber to enable flame observation and two perforated 90-mm-diameter plates are located on the other two sides. A fan is positioned behind each perforated plate in order to mix the gases and generate nearly isotropic and homogeneous turbulence in the central region of the chamber.

The optical system for laser tomography was used to obtain the two dimensional sequential tomograms of propagating flame [3]. For the laser sheet light source, a continuous-wave Nd:YAG laser (5W at 532nm) was adopted. Using three cylindrical lenses, the laser beam was focused into a sheet which had a thickness of under 0.1mm and a width of about 73mm, at the measurement location. TiO_2 powder with a diameter of 0.03~0.05μm was used as the seeding particles. The scattered light was imaged using a high-speed camera (an acquisition rate of 1000 frames/s) with an image intensifier (gate open period =18μs). The spatial resolution in the flame images obtained was 0.23mm.

The experiments were conducted as follows. The mixtures were concocted in the chamber according to the partial pressure of components and then ignited at the vessel center under desired

Table.1 Properties of Mixtures

Mixture	ϕ	Molar Fraction				S_{L0} (cm/s)	a_0 (mm^2/s)	ν (mm^2/s)
		CH_4	H_2*	O_2	N_2			
M07-15NH00	0.7	1.00	0.00	2.86	11.14	15.38	21.03	15.54
M07-15NH04	0.7	0.60	0.40	2.00	9.40	15.10	23.27	15.97
M07-15NH06	0.7	0.40	0.60	1.57	8.49	14.83	24.84	16.28
M07-15NH10	0.7	0.00	1.00	0.71	7.14	15.26	29.24	17.16

*H_2 addition rate δ_H

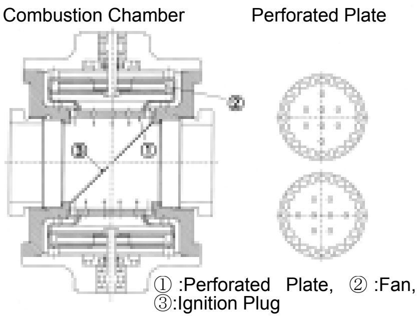


Fig.1 Cross-sectional view of combustion chamber

turbulence intensity and atmospheric condition where the initial pressure and temperature were about 0.101MPa and 298K, respectively. The turbulent combustion experiments were done under the turbulence condition with a fixed fan speed being 1000rpm, where the turbulence intensity u', the longitudinal integral length scale L_f, the Taylor's micro scale λ_g, the Reynolds number based on L_f, Re_L, and the ratio of u' to the laminar burning velocity u'/S_{L0} were about 0.35m/s, 2.8mm, 1.8mm, 60 and 2.3, respectively. The sequential tomography for each mixture in Table 1 was repeated three times for the laminar combustion and over five times for the turbulent combustion at the same condition, respectively. In this study, only the upper part of images from the center of chamber was analyzed.

Properties of Mixtures

The mixtures used in this study are shown in Table 1. They have nearly the same laminar burning velocity (about 15cm/s) by adding nitrogen to hydrogen added methane-air mixtures, with four different rates of hydrogen. In Table 1, S_{L0} is the laminar burning velocity measured by the pressure history of combustion [1-3], a_0 the thermal diffusivity, ν the kinematic viscosity and ϕ the total equivalence ratio based on the numbers of carbon and hydrogen atoms of two fuels (=[(x+y/4)(1-δ_H) + δ_H/2]/X_0), where the mixture composition is expressed as $(1-\delta_H)C_xH_y + \delta_H H_2 + X_0 O_2 + X_N N_2$ and δ_H represents the rate of addition as the volume fraction of hydrogen among the total fuel gases.

Figure 2 shows the measured turbulent burning velocity S_T as u' being varied for mixtures in Table 1. Clear difference in S_T at the same u' can be seen among mixtures with different δ_H, even under nearly the same S_{L0}. The values of S_T at the same u' increase monotonously as δ_H increases.

RESULTS AND DISCUSSION

Observation of Turbulent Flame

Figure 3 shows the temporal evolution of the upper part flame-front contours of the sequential tomograms of turbulent flame for different δ_H at u'=0.35m/s. The flames can be observed to be wrinkled having a continuous flame front, despite of δ_H. The flame fronts also show an interesting movement as observed in previous studies [3]: the active part and the inactive part can be observed on the turbulent flame front. The former and the latter well correspond to the convex part toward the unburned mixture

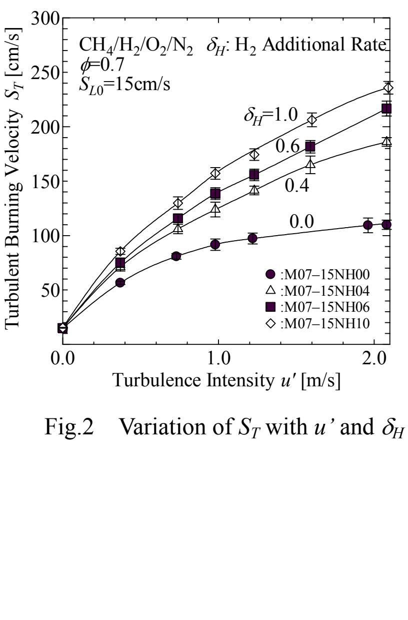
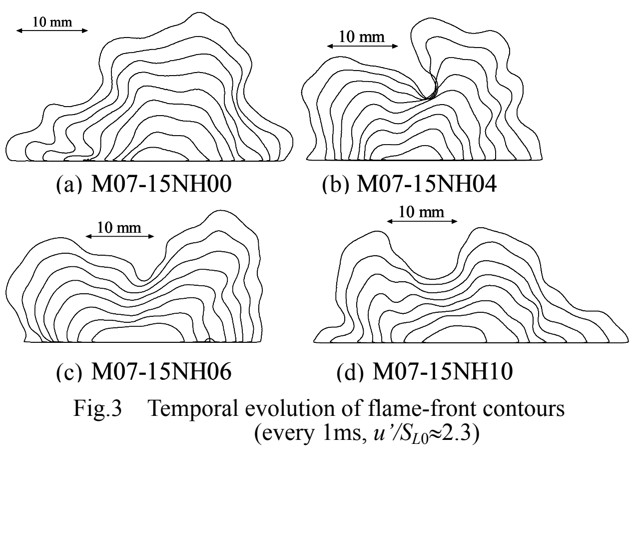


Fig.2 Variation of S_T with u' and δ_H



(a) M07-15NH00 (b) M07-15NH04

(c) M07-15NH06 (d) M07-15NH10

Fig.3 Temporal evolution of flame-front contours (every 1ms, u'/S_{L0}≈2.3) and that toward burned gas, respectively.

Analytical Procedure

In order to investigate quantitatively the local burning velocity, the local flame displacement velocity S_F is determined according to the same method as our previous studie [3,4]. An outline of the procedure is as follows. In the first place, each flame front position can be detected as discrete points (pixels), using appropriate threshold. Then, the curvature $1/r$ at each point can be calculated by vector product and geometrical procedures. The curvature of the convex part toward the unburned mixture is defined as positive. In the next place, the local flame propagation speed V_F at each point can be obtained using two sequential image frames. V_F can be calculated based on the flame travel period and the flame movement distance. It was assumed that the direction of flame front movement was right-angled to the tangential line on the point of flame front. Finally, the S_F is approximated by the following Eq. (1):

$$S_F = (\rho_b/\rho_u)\, V_F \qquad (1)$$

Where ρ_b and ρ_u are the density of burned gas and unburned mixture, respectively, at 0.101MPa.

The local flame displacement velocity might be affected by the progress rate of flame propagation, because the pressure in the combustion chamber increases slightly with the flame propagation. In order to remove this influence, a means, which was the same as the previous studies [5,6], was adopted. For the discussion of the analyzed results, the flame images, which are taken at the same condition as the progress rate $(R_A/R_C)^3$ being about 0.018, are used. Where R_A and R_C denote the equivalent radius based on the burned area of 2D flame image and that based on the chamber volume, respectively.

Local Flame Displacement Velocity

Figure 4 shows the probability density function (pdf) of the acquired $1/r$ normalized by the preheat zone thickness η_0 ($=a_0/S_{L0}$), and the distribution of the acquired S_F normalized by the S_{L0} for the turbulent flame at $(R_A/R_C)^3$ being nearly 0.018. Thick broken lines in Fig.4 represent the mean value of S_F on the positive curvature $S_{F,mu}$ and that on the negative curvature $S_{F,mb}$, respectively. From Fig.4, the values of S_F of the turbulent flame are found to be not a constant value S_{L0}, but to be distributed over a

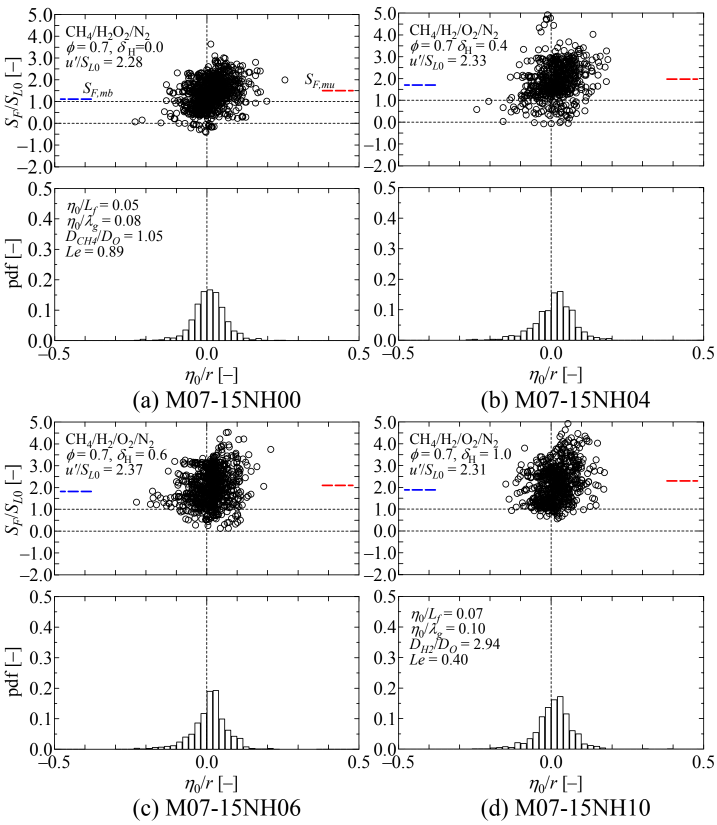


Fig.4 Pdf of the curvature and distribution of the local flame displacement velocity ($u'/S_{L0}\approx 2.3$, $(R_A/R_C)^3\approx 0.018$)

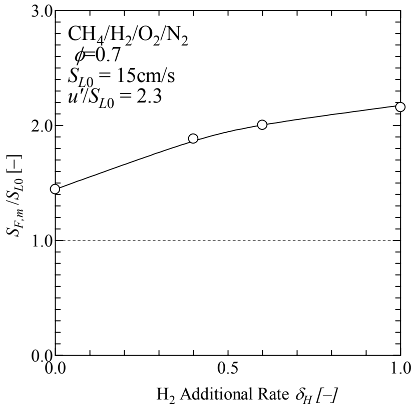


Fig.5 Variation of $S_{F,m}/S_{L0}$ with δ_H

wide range, despite of δ_H. While, the S_F for the laminar flame showed to be almost equal to the original S_{L0}.This experimental result contradicts the conventional concept of turbulent burning velocity, where the local burning velocity is likely to be equal to the original S_{L0} under such weak turbulence condition.

Under this experimental condition, the $S_{F,mu}$ becomes larger than the $S_{F,mb}$. Additionally, as δ_H increases, the $S_{F,mu}$ tends to increase. This trend seems to be explained from the concept of preferential diffusion and Markstein number [7,8] as follows.

The diffusion coefficients of hydrogen and methane are larger than that of oxygen [2], so both fuels can more diffuse to the convex flame toward the unburned mixture due to the preferential diffusion. The local equivalence ratio at this part increases from the original equivalence ratio, leading to the increase of its local burning velocity for the lean mixtures because in the lean mixtures fuel is the deficient reactant. Furthermore, hydrogen has a large diffusion coefficient and a high laminar burning velocity at the same ϕ and N_2/O_2, as compared with methane. Therefore, the local flame displacement velocity at this part can be easily predicted to increase by such properties of hydrogen as δ_H increases.

A linear relationship between the laminar burning velocity and flame stretch has been suggested [7,8]. Faeth et al. [9] have proposed the following relationship for outwardly propagating spherical laminar flames.

$$S_{L\infty}/S_{Ll}=1+MaKa \qquad (2)$$

Where S_{Ll} is the local burning velocity of laminar combustion, $S_{L\infty}$ the value of S_{Ll} when the flame stretch =0, *Ma* the Markstein number and *Ka* the Karlovitz number.

According to the procedure proposed by Faeth et al., *Ma* can be approximated from its temporal contours of laminar flame. As a result, the value of *Ma* varied from 0.1 to -2.4 as increasing δ_H. Therefore, the local burning velocity at convex part toward the unburned mixture at the same stretch can be expected to increase as increasing δ_H.

Figure 5 shows the variation of the mean values of S_F, $S_{F,m}$, normalized by S_{L0} with respect to ϕ. The value of $S_{F,m}$ tends to increase with increasing δ_H. This tendency corresponds well with the result in Fig.2, where the turbulent burning velocity at the same u' increases with δ_H. Thus, it is obvious that the difference in the turbulent burning velocity in Fig. 2 is attributed to the difference in the mean local burning velocity.

CONCLUSIONS

In this study, in order to invstigate the local burning velocity characteristics of the turbulent flame (u'/S_{L0}=2.3) of hydrogen added lean methane mixtures, the local flame displacement velocity S_F has been measured directly by using two-dimentional sequential tomograms. It is found that the obtained S_F tends to increase with the rate of addition of hydrogen, and plays an important roll in the turbulent burning velocity.

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